Search for anomalous tau neutrino appearance in the DUNE Near Detector

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Workshop on Tau Neutrinos from GeV to EeV 2021 (NuTau2021)
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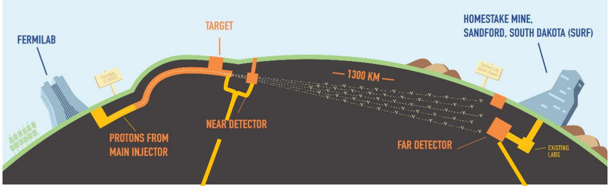
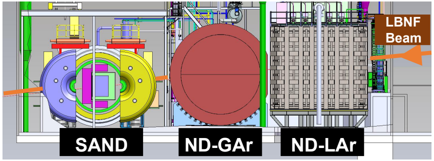
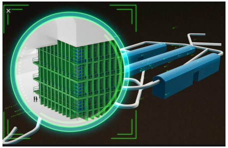
- DUNE : Deep Underground Neutrino Experiment.
- LBL experiment with a baseline of 1300 km (Fermilab to South Dakota).
- DUNE will study $\nu_\mu \rightarrow \nu_l$ oscillation.
- DUNE will use a ν_μ beam provided by the LBNF Facility, with a small ν_e contamination.

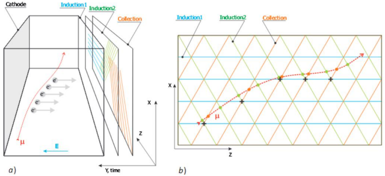


source to ND ≈ 574 m
ND-LAr: LAr TPC, 147 tons

source to FD ≈ 1300 km
FD: 40 kton LArTPC







Liquid Argon Time Projection Chamber

- The capabilities of the **DUNE ND**'s LArTPC + intense neutrino flux from LBNF (1.2 MW) + the short baseline of 574 m → great setup for a **sterile neutrino search**.

Objectives

Main objective

- Distance from neutrino source to DUNE ND is 574 m → In a 3-flavor oscillation model, no ν_τ should be present at the DUNE ND.
- Study of the eventual ν_τ that we may have in the DUNE ND that comes from short baseline oscillations, in a sterile neutrino framework.
- Evaluate the ν_τ appearance sensitivity of DUNE ND by studying ν_τ CC interactions.

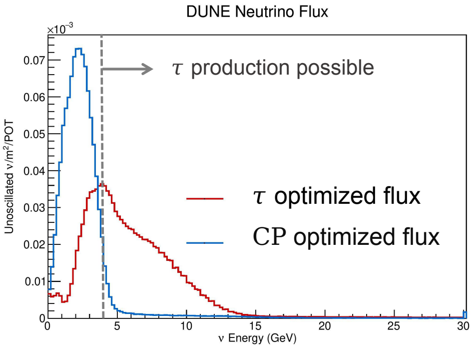
Oscillation probability

$$P(\nu_\mu \rightarrow \nu_\tau) \approx sin^2(2\theta_{\mu\tau}) sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\begin{aligned} sin^2(2\theta_{\mu\tau}) &= 4|U_{\mu 4}|^2|U_{\tau 4}|^2 \\ &= cos^4\theta_{14} sin^2(2\theta_{24}) sin^2(\theta_{34}) \end{aligned}$$

Simulation

- Events were generated using GENIE Neutrino event generator (analysis based on the truth infomation provided by GENIE).



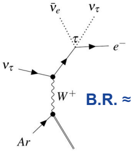
Beam configuration: higher energy neutrino beam optimized for ν_τ appearance in the DUNE Far Detector.

Signal and background separation

Transverse kinematic variables

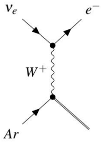
τ decay channels

- Electron channel



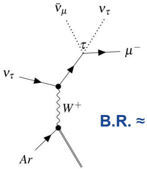
B.R. ≈ 17.83%

ν_τ CC ($\tau \to e^-$)



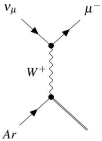
ν_e CC

- Muon channel



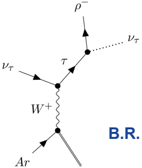
B.R. ≈ 17.41%

ν_τ CC ($\tau \to \mu^-$)



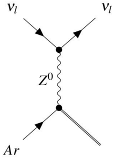
ν_μ CC

- Rho channel



B.R. ≈ 25.5%

ν_τ CC ($\tau \to \rho^-$)

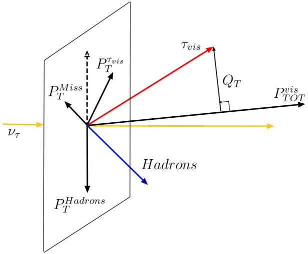


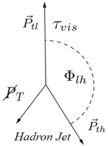
Neutral Current

- Select the ν_τ events from corresponding backgrounds based on their kinematic differences (similar to those used in NOMAD).
  - In ν_τ CC interactions, the τ will decay into some visible products and neutrinos.
  - The neutrinos take away some energy, use missing energy to differentiate.
  - ROOT TMVA : Machine Learning algorithm (Boosted Decision Tree Gradient - BDTG) to separate ν_τ CC from their backgrounds.

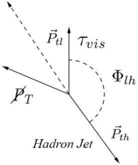
Signal and background separation

Transverse kinematic variables

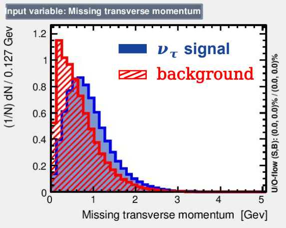


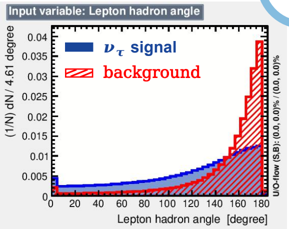


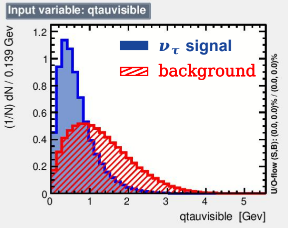
Background interaction products in the transverse plane

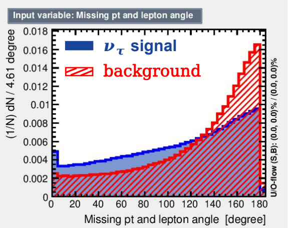


$\boldsymbol{\nu_\tau}$ **CC interaction** products in the transverse plane









Examples of ν_τ signal (blue) and background (red) kinematic variables distribution.

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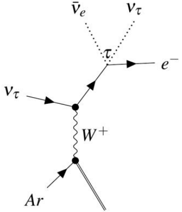
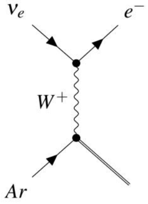
Signal and background separation

Electron channel

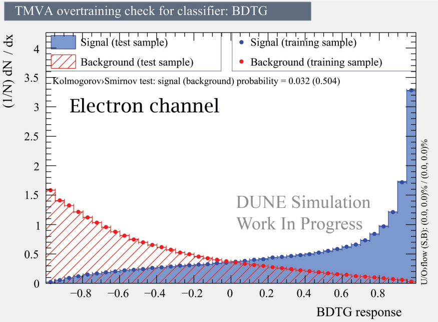
e channel

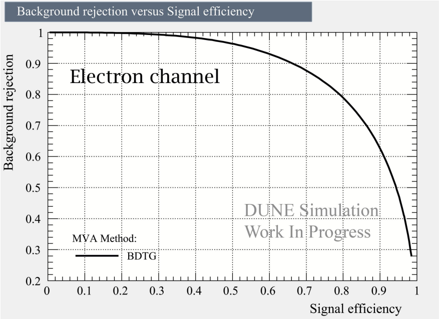


ν_τ CC ($\tau \to e^-$)



ν_e CC





- Reasonable separation of the ν_τ CC from their main backgrounds.

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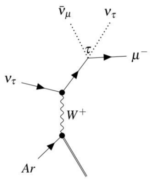
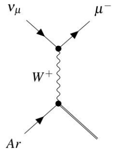
Signal and background separation
Muon channel

μ channel

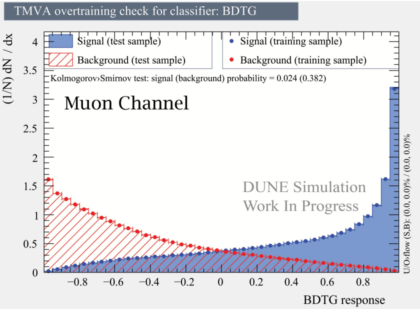


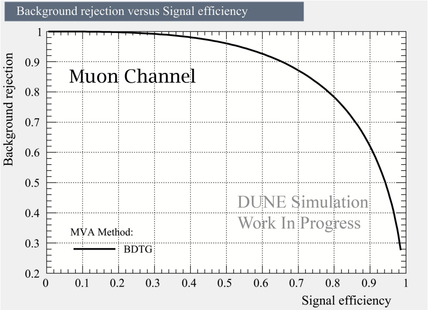
ν_τ CC ($\tau \to \mu^-$)



ν_μ CC

- First, created a classifier that separates muon and pions. μ^- loses energy via Multiple Coulomb scattering whereas π^- loses energy via Coulomb scattering + Hadronic scattering. (Classification using a Recurrent Neural Network).
- Classify ν_τ CC ($\tau \to \mu^-$) and ν_μ CC using transverse kinematic differences.





- Reasonable separation of the ν_τ CC from their main backgrounds.

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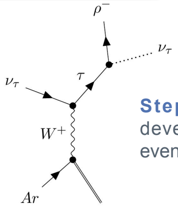
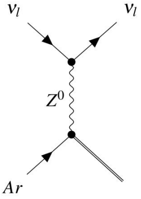
Signal and background separation

Rho channel

ρ channel



ν_τ CC ($\tau \to \rho^-$)



Neutral Current

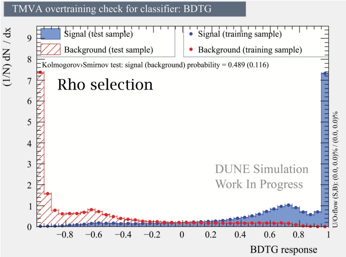
Steps: develop a ρ selector, then develop a classifier that separates NC events from $\nu_\tau(\tau \to \rho^-)$.

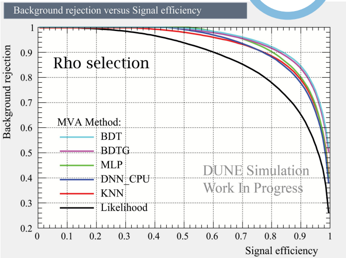
- Signal (true ρ)

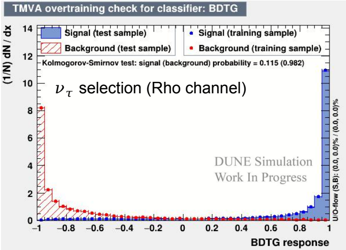
$\rho^- \to \pi^- + \pi^0;\ \pi^0 \to 2\gamma$

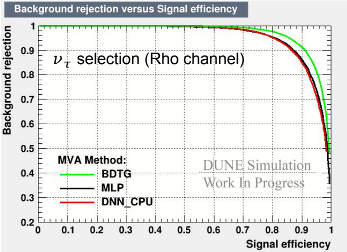
- Background (false ρ)

any $\pi^\pm + \pi^0$ pair that doesn't come from a true ρ^- from the hadronic system or τ decay.









Smearing

- To evaluate selection efficiencies and sensitivity, the case where some smearing is applied to the final state particles 4-momentum was also considered.

- **Case 1 - without smearing** → In the first case, no smearing was applied to the particles four-momentum but only particles above a certain kinetic energy threshold were considered.
  - protons : above 50 MeV.
  - photons : above 30 MeV.
  - pions : above 20 MeV.
  - no neutrons.

- **Case 2 - with smearing** → In addition to the kinetic energy thresholds above, energy and angular resolution smearing applied to particles 4-momentum.

Species	Threshold [MeV]	Energy Resolution	Angular Resolution [deg]
p	50	± 60 MeV	± 5
$\pi^{+/-}$	20	± 10%	± 2
γ	30	± 10%	± 5
e^-		± 10%	± 2
μ^-		± 10%	± 5

Table : Smearing values based on LArTPC performance in the MicroBooNE Experiment (arXiv:2012.09788v3)

- **In both cases, a systematic uncertainty of 10% was taken into account.**

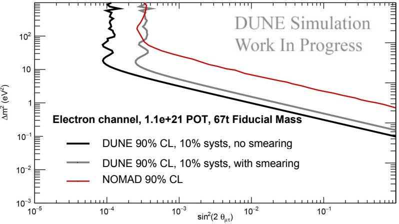
Sensitivity evaluation

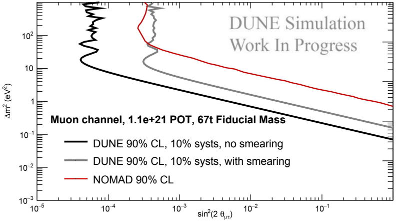
Individual channel

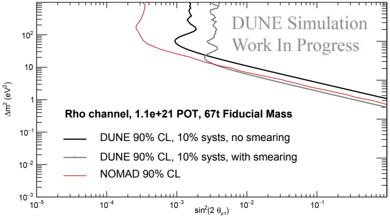
- Sensitivity → based on event counting.
  All events were normalized such that they would correspond to a **1.1e21 P.O.T. and a 67t** fiducial mass.

$$FOM_{systs} = \frac{s}{\sqrt{(s+b) + (\mathbf{0.1}*(s+b))^2}}$$

- Event cuts → region with almost no backgrounds, events scoring a very high BDTG score were selected.







- Electron channel → select events with
  ν_τ BDTG score > 0.995 (non smeared)
  ν_τ BDTG score > 0.9963 (with smearing)

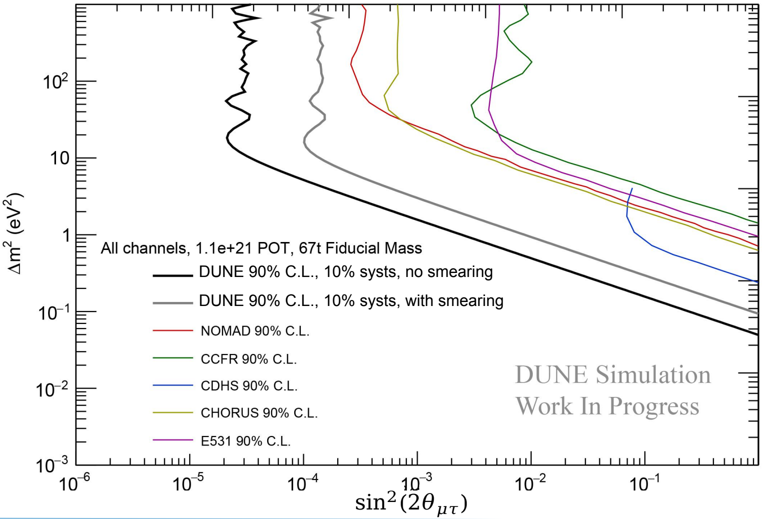
- Muon channel → select events with
  ν_τ BDTG score > 0.995 (non smeared)
  ν_τ BDTG score > 0.9963 (with smearing)

- Rho channel → select events with
  ν_τ BDTG score > 0.99 (non smeared)
  ν_τ BDTG score > 0.992 (smeared)

Sensitivity evaluation

All channels

- **Combined channels**



Conclusion

- Classification using kinematic variables in the transverse plane enables a reasonable separation of the ν_τ signal and background.

- With high BDTG score cuts (region with almost no background) and high-energy beam configuration, DUNE will potentially have leading sensitivity to anomalous short-baseline nutau appearance.

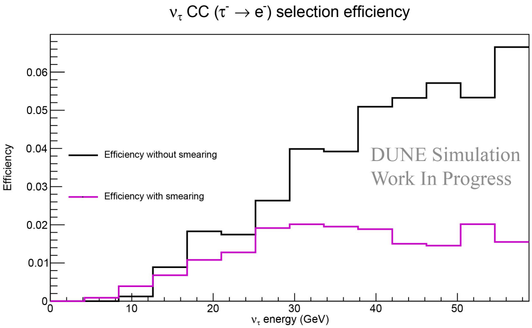
- **Next steps**
  - Consider the other hadronic decay channels such as the single pion channel.
  - Compare results obtained using GENIE Monte Carlo Generator with GiBUU.
  - Determine differences using different τ decayers such as TAUOLA (takes into account the τ polarization).
  - Work on more realistic reconstruction.

Thank you for your attention!

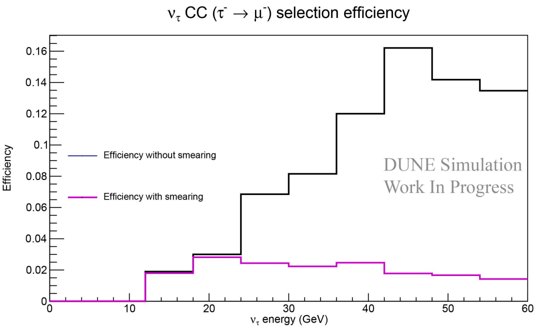
Backup Slides

Backup Slides

- Electron channel

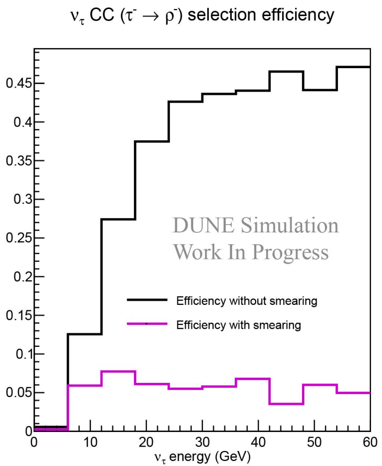


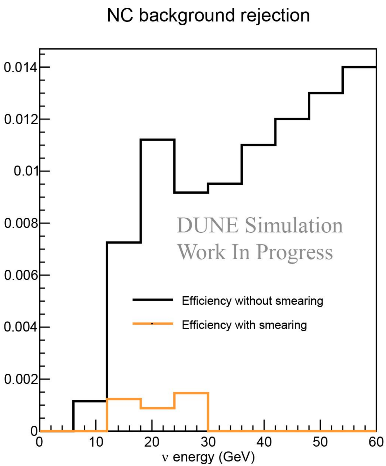
- Muon channel



Backup Slides

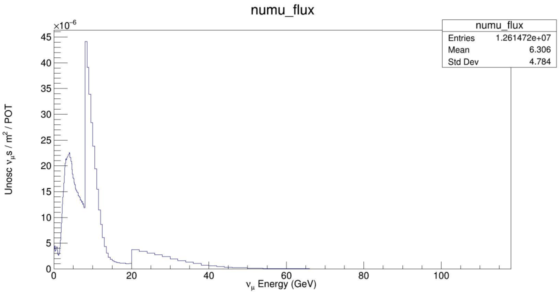
- Rho channel



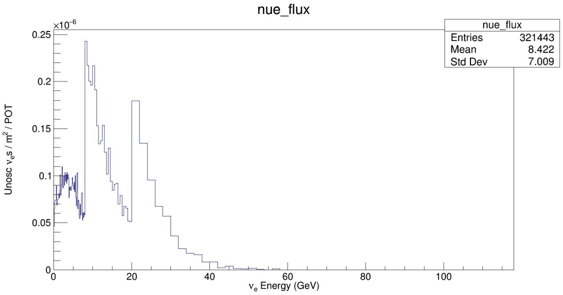


Backup Slides

- Optimized flux for ν_τ appearance in the DUNE Far Detector (Higher energy flux)



ν_μ flux (unoscillated ν_μ per meter squared, per proton on target)



ν_e flux (unoscillated ν_e per meter squared, per proton on target)

Backup Slides

Leptonic channels

- Missing transverse momentum P_T^{miss}.
- Angle between the transverse hadronic system momentum and transverse lepton (tau visible product) momentum φ_{lh}.
- Angle between the missing transverse momentum and transverse lepton (tau visible product) momentum φ_{ml}.
- Lepton transverse momentum P_T^l.
- Hadronic system transverse mometum P_T^h.
- Lepton (tau visible product) energy E_l.
- Total visible energy E_{Total}^{vis}.
- Transverse mass M_T.
- Angle between the neutrino direction and missing transverse momentum $\theta_{\nu m}$.
- Angle between the neutrino direction and the hadronic system $\theta_{\nu h}$.
- Angle between the neutrino direction and the lepton (tau visible product) $\theta_{\nu l}$.
- Ratio between the hadronic system and the total visible energy.
- Component of the lepton (tau visible product) momentum perpendicular tot the total visible momentum.
- Ratio of the transverse lepton (tau visible product) momentum and the missing transverse momentum.

Backup Slides

Rho classification

- Energy of the $\pi^0/\pi^{\pm}$ couple.
- Energy of the $\pi^{\pm}$.
- Invariant mass of the pion.
- Invariant mass of the π^0.
- Pion energy sharing $r_{\pi}^{K} = \frac{E_{\pi}^{K}}{E_{\pi}^{K} + E_{\pi^0}^{K}}$.
- Distance invariant mass and mass $\mathrm{d} = \sqrt{(M_{\pi^0}^{(inv)} - m_{\pi^0})^2 + (M_{\rho}^{(inv)} - m_{\rho})^2}$.
- Angle between the $\pi^{\pm}$ and π^0.
- $\pi^{\pm}$ momentum.
- π^0 momentum.

Rho channel vs NC classification

- All previous variables including those used for the leptonic channels.
- Minimum angle between the tau visible daughter and the hadronic system.
- Ratio between the transverse size of the hadronic system and the full event.